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Polluting emissions standards and clean technology trajectories under competitive selection and supply chain pressure

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Normes d'émissions polluantes et trajectoires de technologie propre sous l'effet de la sélection concurrentielle et de pressions de la filière

Résumé

L'article examine à l'aide d'un modèle de dynamique industrielle l'impact de normes d'émissions polluantes sur les trajectoires de technologie propre de firmes soumises à une sélection concurrentielle et à des pressions de la filière. Le modèle incorpore des faits stylisés sur la relation entre réglementation environnementale, innovation et diffusion. En adoptant une démarche 'history-friendly', l'objectif principal est de mettre en évidence les forces influençant la dynamique de long terme d'une industrie confrontée à des normes d'émissions qui évoluent au cours du temps. L'article propose des orientations quant aux conditions d'efficacité dynamique des normes d'émissions qui tiennent compte de la coévolution des technologies, des exigences des utilisateurs et des structures de marché. Nous montrons que les normes d'émissions non seulement jouent un rôle important dans l'orientation des activités de recherche et d'innovation des fournisseurs mais sont aussi capables de favoriser la diffusion d'innovations environnementales dans la filière. Dans certains cas, les normes d'émissions conduisent à éviter à la fois une situation de verrouillage ('lock-in') du côté des offreurs et une situation d'inertie comportementale du côté des utilisateurs. Les normes peuvent ainsi permettre de préserver une certaine forme de diversité technologique et comportementale. Sur la base des simulations informatiques, nous montrerons que l'efficacité des standards dépend de la nature des normes d'émissions (performance procédé ou produit), de la structure de marché et de la date d'intervention.

Mots-clé : innovation environnementale; dynamique industrielle; pression environnementale au sein de la filière, normes d'émissions

Polluting emissions standards and clean technology trajectories under competitive selection and supply chain pressure

Abstract

Based on a model of industrial dynamics, this paper examines the impact of polluting emissions standards on trajectories of clean technologies implemented by firms subject to competitive selection and supply chain pressure. The model incorporates a few stylised facts on the relationships between environmental regulation, innovation and diffusion. The main objective is to highlight the forces influencing the long term dynamics of an industry faced with evolving emissions standards in a 'history-friendly' way. The paper gives guidance to the conditions of dynamic efficiency of emissions standards taking into account the coevolution of technology, user requirements and market structure. We show that emission standards not only play a significant role in orienting research and innovation activities of supplier firms, but they are also likely to support the diffusion of environmental innovation in the supply chain. In some cases, emission standards lead to prevent both a situation of lock-in on the supply side and a situation of behavioural inertia on the user side. Standards may thus lead to preserve a certain form of technological and behavioural diversity. Based on the computer simulations, it will be shown that the efficiency of standards depends on the nature of performance standards (process or product), on the market structure and on the timing of intervention.

Keywords: environmental innovation; industrial dynamics; environmental supply chain pressure; emission standards

JEL : O33, Q55, Q58

1. Introduction

The importance of supply chain dynamics and its link to environmental pressure in changing firm behaviour has been emphasised by a number of authors. Supply chains have a great potential to exert environmental pressures because they embody many interactions among partners that enable intense and frequent sharing of knowledge about the product and customers' requirements. This opportunity to encounter new knowledge and manufacturing needs is both likely to favour innovation and to facilitate environmental performance improvements. But environmental pressures have a limited influence on many suppliers. In particular, small and low-profile suppliers may lack incentives to change their environmental performance. However Hall [1] argues that environmental supply chain dynamics emerge when environmental pressures are synthesised with supply chain pressures. The author demonstrates that buyer-supplier relationships play a critical role in the decision-making process of most suppliers, which in turn has the potential to stimulate environmental change within the supply chain. Based on case studies in the British and Japanese food retail sector and the British aerospace industry, Hall shows that environmental supply chain dynamics emerge if there is a channel leader with sufficient channel power over their suppliers, both parties have technical competencies, and the suppliers are themselves under specific environmental pressure.

From a policy perspective, it is thus very important to take into account the context in which firms operate, the type of pressures they have to face and the way they interact in the supply chain. Given the number of factors potentially at stake, modelling is tool worth considering, in order to disentangle the effects of policy instruments on the dynamics of an industry.

In a previous work [35] we presented a model of industrial dynamics taking into account buyer-supplier interactions subject to environmental pressures and discussed the results. The present paper examines the dynamic effects of tighter standards on an industry with two vertically related sectors. The previous model is used to exhibit the discriminating role of such policy options within buyer-supplier relations. It is a preliminary exercise concerning the effects of standards on environmental innovation and market structure. The aim is to give guidance to the conditions of dynamic efficiency of emissions standards taking into account the coevolution of technology, user requirements and market structure.

The paper is organised as follows. Section 2 introduces the main stylised facts that are associated with clean technology development and introduces the model. Section 3 presents the model and section 4 examines the impact of tighter standards on the firms' trajectories and the market structure. Section 5 concludes the paper.

2. The general framework

2.1 Some stylised facts about the relationships between environmental regulation, innovation and diffusion

– *Anti-pollution investments undertaken by manufacturing firms to reduce pollution involve different technical solutions (end of pipe, clean) that result from different sources of* *innovation and that correspond to different types of technological change for the adopting firm.*

End of pipe technologies correspond to equipment added at the end of the production process. Clean technologies represent new processes or products that are less polluting than existing alternatives. They involve integrated modifications of the core production process leading to a reduction of pollution at source. They differ from end of pipe technologies because they prevent the by-product of pollution instead of performing curative treatment once pollution has been created.

End of pipe solutions are generally provided by specialists from eco-industry so that innovations are external to the sectors subject to regulation. Given that adoption of clean technologies involves integrated changes, internal capabilities are strongly required. The resulting innovation tends to be idiosyncratic.

For the adopting firm, clean technologies provide opportunities to reduce operating costs by combining less pollution and higher productivity gains while end of pipe technologies do not affect the productive performance of the current process.

– *Regulatory and public pressures are major determinants of clean technologies development.*

In most cases, environmental constraint is initiated by regulatory pressure or public pressure (e.g. from the local community) so that, if firms are to innovate, then they must do so with respect to certain performance parameters [2]. For example, emission limit values serve as a target and give an indication about the direction of technical change. They also serve as a point of reference to indicate minimum requirements that firms have to satisfy in order to comply with regulations.

– *Environmental regulations, if well designed, generally encourage companies to seek innovative solutions that otherwise would remain unexplored. Environmental regulations can thus generate 'innovation offsets' at the process and product levels.*

The application of government policies can take various forms, ranging from command and control to voluntary programs and market-based instruments (e.g. taxes, permits). Various studies have tried to compare the efficiency of these instruments ([3] [4] [5]). It turns out that an unambiguous ranking of policy instruments is not possible. Rather the ranking will depend on several factors such as the cost of innovation, the extent to which innovations can be imitated, the environmental benefit function, the number of polluting firms, etc. In practice, the different types of instruments are complementary tools. Neither regulation nor economic instruments are unsuitable *per se* in stimulating cleaner production. Whether an innovative response will occur depends on the level of the stimulus and the responsiveness of the problem sector to the stimulus.

So it is hardly possible to claim that such and such regulatory measure leads inevitably to more innovation. Moreover, most regulatory constraints generate contradictory effects on innovation. They tend to stimulate certain phases of the process of innovation and to block others. However, as emphasised by Porter and van der Linde [6], 'properly designed environmental standards can trigger innovation that may partially or more than offset the costs of complying with them' (p. 98). Such 'innovation offsets' can thus lower the net costs of meeting environmental regulations and lead to absolute competitive advantage for firms.

Process offsets are linked to higher productivity and product offsets to safer products, lower product costs (for instance from material substitution or less packaging) and products with higher resale or scrap value. The authors also give examples of product offsets characterised by increases in the quality or by new product design for better recyclability and easier assembly.

Willing compliance with environmental regulations may also be a source of competitive advantage for business acting proactively or if the perceived greater care for the environment changes company image among stakeholders, that is, customers, investors, employees and so on, and if this translates into shifts in demand for their output.

– *Clean technologies follow trajectories that result from innovation activities of firms. These trajectories embody multidimensional change involving firm's significant attributes such as: process productivity, product performance, environmental quality of the production process and environmental quality of the product.*

In general, different options for clean technology can be distinguished: such as input substitution and savings, pollution control and prevention technologies, in-process recycling, and finally radically new cleaner processes. Whatever the options, two aspects matter for firms. First, the crucial issue is the degree of discontinuity with respect to existing technologies and activities of production. Second, the technological change associated with the reduction of pollution that a firm may try to implement is likely to affect its productivity. To a certain extent, the more important the technological jump is, the more important the impact on productivity.

So the challenge for firms is to combine an increase in the environmental quality with a rise in productive efficiency. By productive efficiency, we mean the overall efficiency of the production process, i.e. the productivity of inputs and the product quality. Thus when a firm implements a clean technology, the integrated change in its production process will affect its productive efficiency. We argue that the development of clean technology depends on the ability of firms to cope with the following dimensions: environmental quality of the production process, process productivity, product quality and environmental quality of the product.

By product quality, we mean the set of characteristics in the Lancasterian sense [7], [8] that define the users' needs. This dimension turns to be particularly crucial in the analysis of clean technology. Indeed, changes in the production process due to clean technology adoption are likely to have repercussions on the characteristics of the product. The main issue is to determine how the product performance is altered by the adoption of clean technology but also to cope with environmental requirements that will manifest themselves not only at the production stage but also during the use and end-of-life stages of the product.

The difficulty for firms lies precisely in the multidimensional change associated with clean technology adoption. The dimensions outlined above tend to be closely interrelated and may exhibit technological complementarities ([9], [10], [11]). Technological interrelatedness creates demand externalities such that new products, in order to be successfully adopted and eventually implemented, have to fit technically into existing infrastructures and stocks of capital goods. In some way, innovation offsets at the product level point to the need for firms to take care of the induced effects on the product which is manufactured with new cleaner production processes. A good management of the complementarity between the integrated change in the production process and the users' needs appears to be crucial for a successful implementation of a clean technology. Indeed complementarity requirements between the old technology, the new one and the users' needs are likely to represent a strong constraint for firms in their process of clean technology adoption.

– *Environmental R&D aimed at improving environmental performance of processes and products is essential for firms to adapt to environmental demand.*

Scott ([12], [13]) argue that standards bring public pressure to bear on polluting companies, and because of that pressure, those companies then find that investment in R&D for new process technologies to reduce pollution is worthwhile. He tests the empirical validity of this view by examining US industrial firms' R&D efforts aimed at developing new process technologies to reduce the emissions of the hazardous air pollutants identified in Title III of the Clean Air Act Amendment of 1990. He shows that the presence of Title III emissions problems is associated with greater R&D expenditures to reduce toxic air emissions in manufacturing processes[1].

Scott distinguishes between three types of environmental R&D: background research, which concerns the study of the processes creating the toxic emissions, process R&D, which focuses on the process technology to be used by firms in their production, and finally product R&D, which is mainly on the products produced with cleaner technology and those that will have lower toxic emissions when used. Scott's analysis indicates that 23.9% of the industrial R&D performed by firms is related to improving the environmental performance of their products or processes. This aspect is important in order to stress the magnitude of environmental R&D. The results also emphasise that firms tend to consider the different types of environmental R&D (background research and R&D on processes and products) as overlapping. Firms tend to consider environmental R&D as an integrated whole, though they are able to distinguish between the three types of R&D defined by Scott [13]. The results also reveal that environmental R&D is mainly financed by firms and performed independently. In their answers, firms suggest that in general environmental R&D is less or about as costly and risky than other R&D projects.

In the aforementioned areas, environmental R&D appears to exhibit similar properties to R&D projects in general. The main specificity of environmental R&D is that it is more often a response to government regulation, in particular for process and product R&D.

Although Scott [13] develops a description of the portion of industrial R&D aimed at solving environmental problems, the author notes that much work in the area of environmental problems is done with routine engineering that moves companies along a learning curve for essentially the same technologies or perhaps, in some cases, actually develops new technologies. The work is within companies' engineering budgets rather than their R&D budgets. This echoes the arguments emphasised by many authors of economics of innovation (among others [14]; [15]) that innovation partly relies on formal R&D but also on more informal practices such as learning.

As outlined by Scott, despite the fact that apparently much is done to clean up toxic air emissions with routine engineering, R&D provides a different approach that is not simply moving along a learning curve for known processes or relegating new developments to routine engineering. By undertaking R&D, the company focuses on risky investments to

[1] See also [16], [17], [18].

develop new approaches, and it puts into play a part of the corporation with its identity and success bound up with the development of those new approaches rather than with incremental improvements to existing processes.

– *Opportunities of environmental improvements are differentiated according to the technological and scientific paradigms which guide innovation activities of firms.*

According to Dosi, a 'technological paradigm' is defined as a 'pattern' for solution of selected techno-economic problems based on highly selected principles derived from the natural sciences [14]. A technological paradigm contextually defines the needs that are meant to be fulfilled, the scientific principles utilised for the task and the material technology to be used. In other words, the specific body of knowledge underlying a paradigm guides the search and development activities required by the innovative process.

So, technological paradigms define the technological opportunities for further innovations but also some basic procedures on the way of exploiting them. Thus they also channel efforts in certain directions rather than others: a technological trajectory is the activity of technological progress based on the economic and technological trade-offs defined by a paradigm. These concepts point to the idea that innovative activities are strongly *selective*, *finalised* in rather precise directions and often *cumulative*.

Traditional examples of paradigms are given by the internal combustion engine, oil-based synthetic chemistry or microelectronics. With the continuous rise in environmental issues and regulations (European Directives, anti-pollution taxes etc.), major changes in the set of technological opportunities offered to firms are also likely to occur. For example, non-chlorinated chemicals, bio-fuels and energy production based on renewable resources (wind or solar energy) can be considered 'green' paradigms that compete or coexist with more conventional ones [19]. These paradigms are grounded on radically new materials and heuristics that call into question the existing body of knowledge.

Thus by considering that paradigms predefine the patterns of solution and point the whole innovative process in particular directions, the switch to a new 'green' paradigm may have particular consequences like competence destroying effect, switching costs (particularly high if strong discontinuity is involved and a new experience phase is required) etc. Innovation offsets may thus be very small or incomplete.

– *The presence or absence of supply chain pressure has been found to significantly influence the environmental performance of companies, including the adoption of cleaner technologies.*

The importance of supply chain pressure in dealing with environmental issues can be explained by the conjunction of two trends: on the one hand there is the rise in environmental regulations with the intention of promoting waste prevention, that put responsibility on the producer, on the other hand there is the supplier's involvement in new product development, in particular for large manufacturers in technology-intensive industries such as automobile, electronics, telecommunication, aerospace, computer and software [20]. In some cases, manufacturers give suppliers the responsibility for improving parts or subsystems custom-made for the manufacturer's products.

Manufacturers are led to take into consideration the life cycle of their products and the nature of demand to be henceforth addressed by the suppliers is modified to take into account some environmental requirements. From the suppliers' standpoint, their innovative capabilities are exercised with relatively little room for manoeuvre as they have to cope with technical matters (increase in product performance, new processes, quality standards) and environmental impacts concerning their own production activities (resource savings, water and air emission reduction, waste) but also those linked to the product to be sold and used later in the production process of the final good. In particular, by specifying requirements of environmental quality to the suppliers, manufacturers exert pressure leading to the suppliers repositioning themselves by relearning the design, production and/or sale of their products along lower impact lines [21].

While manufacturers give incentives to invoke voluntary efforts for innovation, they also impose on suppliers implicit threats such as exercising their superior bargaining power in transaction deals and/or substituting their partners with other suppliers if their partners' innovation efforts do not meet their expectations [22]. Thus, supplying partners feel a heavy pressure to innovate. Eventually, this pressure drives the effort of innovation on the part of suppliers.

Nonetheless, innovative responses of the suppliers are not only demand-driven. The innovative capabilities of suppliers involved in the manufacturers' new product development may also help the latter introduce new designs faster with a lower price or products with a higher quality [23]. Such involvement may thus make suppliers able to eliminate pollution and waste and to suggest possible solutions to decrease environmental impacts of the equipment good to be used by the client.

These arguments stress that if suppliers take into account new requirements like environmental quality, the reason lies in the regulatory and market demand in terms of low environmental impact of product, health and security that manufacturers are instrumental in passing on to their suppliers. However this vision is incomplete since the creation of such demand is also shaped by the strategies of suppliers. This is through the technologies they have partly adopted and partly created to be able to differentiate their products and/or to reply to the differentiated offer of their rivals that suppliers can integrate or improve one or the other performance characteristics for which the level of requirement of the clients has increased.

– *The firm's response to demand of environmental quality is different according to whether final consumers or other firms are addressed. Environmental chain pressure is more active because of the contractual commitments between firms.*

According to a CREDOC consumption survey [24], environmental damage is part of the growing concern of final consumers, whether in France or in the rest of Europe. This phenomenon has been accompanied with strong consumer expectations regarding ecological guarantees. In situations of a quality crisis or a striking ecological event (chemical accidents, environmental groups actions etc.), the already growing attention of final consumers is amplified. In such cases, consumers are led to search for information about the origin and the production methods of the product they want to buy. If doubts emerge on the product quality then the relevance of information used by far to select the product is called into question. This makes the consumer attentive to information that was not taken into account before. Thus, the consumer's attention is higher and can be directed towards alternative suppliers that intend to integrate these new environmental requirements. However, in spite of a growing attention toward environmental issues, only some categories of products are the subject of a real demand from green consumers and are likely to develop on green market niches. This is the case for agro-food products for example.

Environmental differentiation of products is not simple since environmental quality raises the specificity of being hardly testable by the consumer [25]. Even if consumers are informed about polluting emissions of products, they are not able to evaluate environmental quality and to punish the products they assess as less environmentally friendly. This is the reason why ecological guarantees such as environmental labelling for example, are needed to enable an appropriate selection of products. These guarantees do represent an incentive to buy for a number of consumers [24]. In order to cope with this difficulty to objectively evaluate environmental impacts of products, manufacturers of final products undertake communication activities aiming at building consumer trust. Companies can also engage in more targeted actions towards consumption or environmental groups and local communities. Nevertheless, demand for environmental quality originating from final consumers remains uncertain or inactive for most final products. Thus, pressures from consumers do not necessarily make product manufacturers and their corresponding production branches more aware.

The nature and the magnitude of effects associated with the development of clean technologies are different in the case of inter-firm relationships, especially between two firms located at different stages of a production process. Pressures from industrial clients tend to represent a credible threat for suppliers and subcontractors. Indeed, both types of firms are linked by contractual commitments that incorporate requirements and quality clauses that make the duration of the relationship conditional on honouring such commitments. This constitutes both a way to control and to sanction the partners. Those requirements generally bring the suppliers and subcontractors to undertake important investments. As a consequence, demand for environmental quality from clients is likely to give incentives to suppliers to invest in clean technologies.

In some industries like the automotive one, manufacturers have initiated a movement of certification that stimulates the suppliers to do the same. The implementation of environmental management systems (EMS) and audits by suppliers, in order to get the certification according to the ISO14000-type standards, may become an advantage for engaging in contractual relations with some manufacturers. Indeed the certified supplier gives the proof of its ability to provide its clients while complying with some standards of environmental performance. But, though environmental chain pressure can decisively affect suppliers' behaviour regarding environmental compliance, environmental criteria for selecting suppliers remain weak and there is little attempt to audit supplier performance [26].

2.2 A representation of supply-demand interactions in an industry subject to environmental regulation

Figure 1 gives a schematic view of the basic interactions we have considered in our analysis of clean technologies development.

Insert Figure 1

An industry with two vertically related sectors in interaction is depicted. A population of n suppliers (i=1,…,n) constitutes the supply side and the demand side is represented by a population of m clients (j=1,…,m). Suppliers produce differentiated equipment goods that are assumed to be used in the future production of final goods. Only intermediate demand is explicitly taken into account however.

Clients evaluate the equipment good according to four user's characteristics in the Lancasterian sense: price, product performance, and environmental quality at the process level and at the product level (labelled P, Am, Ip, Im respectively). According to Lancaster, a good contains a bundle of performance characteristics or attributes. Suppliers fit into competition by offering the combination of characteristics that they think they are more attractive to clients than those offered by their rivals. Clients have different preferences and requirement levels for each product characteristic.

Purchase decisions of buyers take into account the preferences (arrow 1) and the 'global' performance of suppliers (arrow 1’) which is given by the level for each characteristic and the market share. These elements are used by clients in their evaluation of suppliers.

When suppliers are selected, they are given some information on the current profile of their buyers (arrow 2). This information will be used to direct R&D investments of suppliers. Additionally, competition among suppliers to get dominant position on the market will influence R&D allocation (arrow 2’).

Innovative activities carried out by suppliers lead to improved average industry performance, which will modify requirement levels of clients (arrow 3), in proportion to the priority they assign the considered characteristics (arrow 3'). Such requirement levels intervene in the decision to leave a supplier at the time of product replacement (arrow 4). In case of non compliance with client requirements, there is defection and the client will turn to the other suppliers still active in the market. In the case of satisfaction, the client will renew the purchase among the same supplier.

3 A brief overview of the model

Based on the stylised representation of an industry constituted by firms subject to competitive selection and supply chain pressure, we have built a model of industrial dynamics. Such models are characterised by their focus on the dynamic co-ordination of diverse behaviours. Moreover, the analysis that we propose is linked to the particular assumptions we have considered for clean technologies development so that our model is in line with ‘history-friendly modelling’.

3.1 History-friendly modelling

History-friendly models make it possible to analyse what kinds of factors and dynamic processes account for the evolution of different industries. History-friendly analysis has been used to study the evolution of the computer industry [27], [28] and that of the pharmaceutical industry and biotechnology [29]. These models integrate an evolutionary approach based on micro diversity of behaviours and the bounded rationality of decision processes while also placing central importance on a wide variety of devices for co-ordinating and shaping interaction between agents. The relevant evolutionary outcomes are emergent phenomena arising from processes of interaction. An emergent phenomenon is one that arises from the coordination of the activities of agents and creates a pattern of order not contained in the intrinsic properties of those agents.

In such a framework, competition is not seen as a state of equilibrium induced by a particular market structure. Rather it is viewed as a dynamic process that depends on how the micro diversity of firms' behaviours results in changing market positions, and on how competitive advantage is defined and leads to particular patterns of change.

This class of models is of great interest in comprehending the industrial transformation incurred by the manufacturing industry when addressing environmental issues over time. The development of clean technologies by firms in the industry can be closely examined. We focus specifically on the sectors where competitive advantage strongly depends on supply chain management. Indeed, such sectors tend to undergo an increased awareness in environmental issues. For example, regulatory approaches that put the focus on producer responsibility contribute to transmit environmental quality requirements towards upstream activities.

Our modelling explicitly takes into account buyer-supplier relationships. The model deals with a population of rival suppliers in interaction with a population of industrial clients. On the one hand, suppliers modify the characteristics of their product thanks to R&D investments so as to adapt to demand pressures and to acquire competitive advantage. On the other hand, clients' requirements evolve so as to adapt to technological changes and modifications of industrial structures. Environmental pressures are synthesized with supply chain pressures (e.g. price, product quality).

3.2 The equations

3.2.1 R&D investments and innovation activities of suppliers

Each supplier devotes a part of its turnover to R&D activities. The R&D budget of firm i at time t is given by the following equation: $RD_{i,t} = \mu_i.P_{i,t}.B_{i,t}$ (1)

with $P_{i,t}$ the price of the product i at time t and $B_{i,t}$ the install base of firm i at time t. μ_i stands for the fraction of turnover allocated to R&D. The install base of firm i represents the stock of clients that use the product i. By basing R&D expenditures upon the user stock, firms can get rather stable R&D investment.

Let denote $X_{i,t}^h$ the performance level performed by firm i for the characteristic h at time t[2]. The amount of resources allocated to the characteristic h is given by: $RD_{i,t}^h = \delta_{i,t}^h.RD_{i,t}$ (2)

$\delta_{i,t}^h$ represents the rate of R&D investment dedicated to the improvement of characteristic h. We assume that $\sum_{h=1}^{4} \delta_{i,t}^h = 1$.

[2] In the following, X^1 corresponds to the productive efficiency, X^2 to the product performance, X^3 to the environmental quality at the process level and X^4 to the environmental quality at the product level.

The research level achieved for the characteristic h is: $R_{i,t}^{h} = \gamma.RD_{i,t}^{h} + (1-\gamma).R_{i,t-1}^{h}$ (3)

This research level reflects the progressive contribution of the resources dedicated to R&D to the knowledge base of firms. It adaptively evolves to account for learning in knowledge production activities. γ is a parameter determining the speed to which the research level is adjusting to the current R&D budget dedicated to the characteristic.

Innovation is treated as a stochastic process and a two-step procedure is used to determine the innovation output. The first step determines if there is success or not. The second step consists in determining the increase in the new performance that results from the innovation. Thus, for each characteristic, the probability of the value improving depends on the R&D resources allocated to it: $\Pi_{i,t}^{h} = \pi_1 / (\pi_2 + \pi_3.\exp(-\pi_4.R_{i,t}^{h}))$ (4)

π_1, π_2 and π_3 are the limiting parameters of the logistic function. The parameter π_4 determines the speed at which the maximal probability is approached. According to (4), the R&D returns are successively characterised by increasing and decreasing returns[3].

In the case of success, the innovation output is determined by a Cobb-Douglas function that depends on the R&D budget invested on the characteristic ($R_{i,t}^{h}$), the cumulated experience on this characteristic ($E_{i,t}^{h}$) and the distance to the technological frontier that prevails for this characteristic ($X^{h\max}$): $\Delta X_{i,t}^{h} = \eta_0.(R_{i,t}^{h})^{\eta_1}.(E_{i,t}^{h})^{\eta_2}.(X^{h\max} - X_{i,t-1}^{h})^{\eta_3}$ (5)

η_0 is a scale parameter. Parameters η_1, η_2 and η_3 respectively reflect the intensity of R&D impact, of the experience and of the saturation of technological opportunities upon the magnitude of improvement of the characteristic. We assume that $\eta_1 + \eta_2 + \eta_3 = 1$. Hence innovation is a cumulative and firm-specific process.

The experience variable is itself subject to progressive adaptations according to the following equation: $E_{i,t}^{h} = \lambda.(MaxE \times R_{i,t}^{h}) + (1-\lambda).E_{i,t-1}^{h}$ (6)

According to this equation, experience depends on past experience and on the current research level achieved for the characteristic. However the accumulation of experience is limited by a maximum value (MaxE). λ represents the coefficient that weights the experience potential achieved thanks to the current research level on the characteristic.

3.2.2 The product price

The product price is determined by applying a mark-up rate over the production costs. Since our model does not consider explicit production factors, productivity gains that suppliers get by investing in R&D to improve their production process can be used as a proxy for the decrease in production costs. By doing this, we assume an inverse relation between the productive efficiency (the characteristic identified by X^1 in our formulation) and the price.

[3] For empirical justification, see[30].

The equation for the price is thus simply given by the following function: $P_{i,t} = (1+\theta_i).(1/X^1_{i,t-1})$ (7)

with θ_i the mark-up rate of firm i.

3.2.3 Technology space

Technological and environmental opportunities are represented by considering two paradigms (cf. figure 2 below): paradigm 1 with low environmental potential and paradigm 2 with high environmental potential. The first potential represents conventional production practices with low opportunity along the environmental dimension whereas the second technological space offers higher opportunities since it is based on radically new production practices that reduce pollution at the source.

Insert Figure 2

We assume that the switch carried out by a firm in the paradigm with high environmental potential leads to the following effects:

- A shift in the frontier achievable on the dimension 'environmental quality of process' (X^{3max2}), the frontier on the dimension 'productive efficiency' remaining unchanged (X^{1max2}). However, we also consider that a threshold exists in terms of productive efficiency (X^{1max1} in figure 2) gained by firms that evolve in the first paradigm. The experience variable (E) will decrease when the first limit (X^{1max1}) is crossed and higher opportunities will be available (X^{1max2}).
- A drop in the product performance (X^2).
- A decrease in the cumulated experience (E).

3.2.4 Decision rules of clients

Three decisions concern the clients: the purchase of a product, the moment to replace the product and the decision to leave or keep the same supplier.

a) Purchase

Each client j is characterised by a probability of buying the product i as follows: $\Pr oba^i_{j,t} = (1/P_{i,t-1})^{x^1_j}.(X^2_{i,t-1})^{x^2_j}.(\widetilde{X}^3_{i,t-1})^{x^3_j}.(\widetilde{X}^4_{i,t-1})^{x^4_j}.(MS_{i,t-1})^e$ (8)

with x^1_j, x^2_j, x^3_j and x^4_j the preference that client j attributes to the corresponding characteristics. These preferences reflect the positioning that client j adopts in the final good market. The features of the positioning are reflected in the weight assigned to each characteristic by the client. In order to limit the range of these parameters, we set them so that their sum equals to 1. Parameter e expresses the intensity of 'bandwagon effect' that a supplier with high market shares may exert on clients[4].

So clients take into account the characteristics they perceive from the suppliers but also the supplier's market shares. Market shares in the purchase decision exhibit two things. First, in a context of uncertainty and imperfect information, an important source of information comes from previous users. An agent who wishes to buy a new product will tend to refer to the choice made by the other users in the past [27]. Market shares give such an indication. So, mimetic behaviour on the user side can help to choose among alternative suppliers. Second, links between suppliers and clients for product innovation require mechanisms allowing positive outcomes for both parts. The implementation of these mechanisms and the costs they incur may be so strong that they reduce transaction alternatives and entail high switching costs. So market shares in the purchase decision enable to account for switching costs that would prevent a client to choose alternative suppliers.

Market share of firm i at period t is determined with its install base, i.e. with its actual users' stock: $MS_{i,t} = B_{i,t} \Big/ \sum_{i=1}^{n} B_{i,t}$ (9)

b) Product replacement

Each client replaces its product after T periods, with T settled randomly between 1 and 10. Under this hypothesis, clients need a certain period of use before buying a new product, which is generally the case with intermediary or equipment goods. By doing this, a distinction is made between the client stock (the install base) and the current sale flow of a supplier since we assume that clients have different purchase rhythms and thus do not renew the product at each time period. In this case, each supplier has to manage the user stock of its own product even if, for example, its current sale flow is zero.

c) Defection

In order to account for the defection/voice decision, the following procedure is formalised: if all the requirement levels of client j are satisfied, then there is continuation of the relationship with the current supplier i; else, defection occurs and a new supplier is chosen among those remaining on the market (cf. purchase procedure a).

At the time of product replacement, the client compares the performance achieved by its current supplier for each characteristic and its own requirement levels. If all the requirement criteria are fulfilled, then the client keeps the same supplier and renews its purchase among it. In this case, the corresponding supplier records a sale ($N_{i,t} = +1$) while its install base remains unchanged. On the contrary, if the client leaves its supplier, this is because the client is not satisfied with the supplier's performance on at least one of the four characteristics with regard to its minimum requirements. In this case, the corresponding supplier loses one client ($B_{i,t} = -1$).

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[4] We consider random draws for X^3 and X^4 when buyers have to read the score of these characteristics and choose which product to buy (the tilde refers to that). This is related to the fact that buyers have limited capabilities to perceive environmental quality of production activities or products. The perceived value comes from a draw in a normal law with average, the level achieved by the supplier for the considered characteristic, and with standard deviation (σ), a parameter calibrating the error degree of environmental quality evaluation.

3.2.5 Inter-firm interactions

Inter-firm interactions involve three mechanisms: the transfer of information from demand to supply, the updating of R&D investment allocation and the evolution of requirement levels.

a) Transfer of information

Two types of data are used to guide supplier's R&D allocation:

- the product characteristics that are both a priority for the clients and represent a source of technological lead for the supplier. Formally, priority characteristics are those endowed with the highest weight. Characteristics with a weight greater or equal to 95% of the maximum weight are considered to be priorities. To be one of the leaders, we assume that a firm has to reach a performance level greater or equal to 95% of the highest performance on the considered characteristic. In total, a positive score ($Z_{i,t}^{h} = +1$) is given to characteristics that meet these two conditions;
- the product characteristics for which supplier performance is inferior to that required as a minimum by clients and which are likely to cause defections at the end of the product use period. Formally, a negative score ($W_{i,t}^{h} = +1$) is registered for the characteristic with a performance level below the one required by the client.

b) Evolution of the allocation of R&D investment of suppliers

On the base of the information gathered by the supplier i during each purchase cycle, the allocation of R&D among the characteristics is updated. Let $RDIndex_{i,t}^{h}$ denote the R&D index for the characteristic h that is used in the evolution of R&D rates. It is subject to progressive adjustments according to the following equation:

$$RDIndex_{i,t}^{h} = (1-\alpha).RDIndex_{i,t-1}^{h} + \alpha\left((\beta.Z_{i,t}^{h} + (1-\beta).W_{i,t}^{h}) \Big/ (\beta.\sum_{h} Z_{i,t}^{h} + (1-\beta).\sum_{h} W_{i,t}^{h}) \right)$$

(10)

where $Z_{i,t}^{h}$ represents the positive score assigned by the supplier i to the characteristic h when this characteristic is both a priority for its current clients and a source of technological lead compared to its direct competitors. $W_{i,t}^{h}$ represents the negative score assigned by the supplier i to the characteristic h when the performance achieved on this characteristic is above the requirement level of its current clients. α is the speed to which R&D index adjusts to information raising from the sales performed by each supplier. β stands for the relative importance attributed to the positive indicators compared to the negative ones. R&D indices are then normalised such that: $\delta_{i,t}^{h} = RDIndex_{i,t}^{h} \Big/ \sum_{h} RDIndex_{i,t}^{h}$ (11)

c) Evolution of minimum requirements of clients under the influence of technological advances in the industry

The requirement levels evolve through time according to average performance of industry and to the importance attributed by the clients to the considered characteristic. The following equation gives the dynamics of requirement level assigned by the client j to the characteristic h[5]: $levelX^h_{j,t} = levelX^h_{j,t-1} + \varepsilon.(\max(0, x^h_j.(\overline{X}^h_t - levelX^h_{j,t-1})))$ (12)

with $\overline{X}^h_t$ the average performance of the industry for the characteristic h weighted by suppliers market shares, i.e. $\overline{X}^h_t = \sum_{i=1}^{n} MS_{i,t}.X^h_{i,t}$.

Parameter ε represents the difference share between average performance and requirement level that is passed on the evolution of aspiration levels, x^h_j the preference (weight) attributed by the client j to the characteristic h.

3.2.6 Exit process

Exit of suppliers occurs both when the install base is equal to 0, i.e. the user stock of the supplier is exhausted, and when the sales are equal to zero for a minimum of four periods. In this case, the current turnover does not permit any R&D investments and innovation. In the model, there is no entry of new suppliers or new clients.

4. The effects of emission standards upon firms' trajectories and industrial structures

The model we propose in this paper incorporates mechanisms that give the industry the capacity to self-organise, i.e. to cause a global structure to emerge that did not exist previously and that may appear as the outcome of various interactions between agent populations [31]. A self-organisation process such as this implies that an economic system can, by starting from the same initial situation, evolve differently depending on the uncertainties of its history. This leads us to emphasise which possible scenarios of industrial dynamics are likely to be generated under the set of assumptions we have considered. Such scenarios are used to explore the impact of tighter standards upon the trajectories of firms and upon the market structures.

4.1 The reference configuration

4.1.1 Initialisation and simulation trials

Initial values of parameters and variables are presented in detail in the appendix (tables 1 and 2). We have considered a population of 12 suppliers interacting with a population of 200 clients. Each client makes a purchase during the first period and then renews the purchase of the product after T periods with T settled randomly between 1 and 10. Each simulation run comprises 500 iterations[6].

[5] We only explicit here the formal equation of the dynamics of requirement levels for the quality characteristics (X^2, X^3 and X^4) which are expected to increase. The equation for the maximum price is slightly different and adapted so as to take into account the decreasing updating of its level.

[6] Time series analyses conduced over more than 500 periods showed that the industrial structure converges on an asymptotic state characterised by a high level of market concentration after 500 periods.

Suppliers are initially identical so that the differences likely to emerge from the dynamics of the system result from the competition process and from their specific interactions with the set of clients. Whatever the characteristics, the initial technological level is set to 1. Each characteristic is endowed with an upper limit that represents technological constraints. We assume the coexistence of two paradigms differentiated in terms of potential for improving environmental quality of the process (cf. figure 2).

Two distinct groups of clients are considered. Differences across both groups come from different sets of preferences and different willingness to pay. The first group of clients (G1) strongly weight environmental characteristics whereas economic characteristics such as price and product performance are weakly weighted. The inverse is assumed for the second group of clients (G2). This group is dominant in the market and initially represents 80% of demand.

Group 1 is supposed to have a relatively high maximum price, consistent with the assumption that this type of clients is willing to pay a higher price for products meeting environmental criteria. Group 2, which pays great attention to price and product efficiency, has a relatively low maximum price. The point is that a client that wants to adopt an environmental positioning on the final good market, will consequently make stronger demands on environmental characteristics than on price to its suppliers since it will allocate a greater budget in order to buy such a product. This is why weightings and maximum price are set in consistency with the strategic positioning of each type of client.

The requirements in terms of minimum performance of product are assumed to be identical for both groups of clients. As to the requirements in terms of minimum environmental performance, these are the same for both groups since they are enforced by regulatory authority and apply homogeneously to the industry. However, given the dynamics we have considered, the various requirement levels evolve differently across the client groups in accordance with their sets of preferences and with the average progress of the industry.

The structure of the model is such that no analytical solution exists and only simulation trials can enable us to infer the properties of the model. The inductive analysis of the properties of industrial dynamics aims to explain the patterns of interaction between firms and the characteristics of evolution of the industry. Some precautions have to be taken however in order to stress emergent properties. Indeed, the stochastic character of the dynamics raises the problem of validating the simulation results. One simulation alone does not prove the existence of an emergent property since the system is characterised by several random processes. Furthermore properties are obtained under specific initial conditions and parameter values. Therefore, in order to guarantee some robustness of the results and to stress the regularities of the industrial dynamics [32], a high number of simulation runs and a sensibility analysis of parameters need to be carried out.

As we are focusing on the impacts of environmental standards on industrial dynamics in this paper, we have limited the analysis to one set of parameters, the so-called reference configuration. The results come from 50 series of simulation, of 500 periods each. But in order to better observe the forces behind the system dynamics, we have also examined individual series of simulation that characterise the most likely scenarios and summarise the behaviour of the simulation model. These individual series will be used to study the impact of standards. Finally, to implement the model, we have used the programming system LSD (Laboratory Simulation Development) developed by M. Valente at the IIASA[7].

4.2.2 Two emergent market structures

Two alternative types of industrial structure emerge in the long term:

- **A concentrated structure constituted by firms with a specialisation on price and product performance**. The firms that survive after 500 periods are characterised by a high R&D investment in the economic performance of processes (productive efficiency) and products (product performance). These firms are labelled PROD firms. They succeed in complying with environmental regulation. However these firms do not change paradigm. This scenario emphasises the emergence of a monopolistic or oligopolistic structure, with firms oriented toward the improvement of price competitiveness and product performance and evolving within the paradigm with low environmental potential. Over a battery of 50 simulation runs, 26 series correspond to this scenario. We call it '**scenario HO**' for homogeneous oligopoly.

- **A concentrated structure where a 'green' market niche coexists with a low number of dominating firms characterised by a technological lead on price and product performance.** The 'green' market niche results from the survival of a firm characterised by a high environmental R&D investment that enables it to change paradigm, but also by a high price and a low product performance. This scenario emphasises market segmentation with the emergence of a green market niche dominated by a firm that mainly orients its R&D activities toward the improvement of environmental quality – which we call ENVI firm- and that evolves in the paradigm with high environmental potential. This niche coexists with (at least) one PROD-type firm specialised in price and product performance which dominates the market. Over a battery of 50 simulation runs, 20 series corresponding to this case have been observed[8]. We call it '**scenario MS**' for market segmentation.

Scenario HO exhibits 'design dominant' features. Indeed, if we refer to the Abernathy-Utterback model of the innovation life cycle [33], the first phase is characterised by a market convergence to a single design or 'dominant design'. An industry shake-out occurs and a phase of process innovation can start. The final phase is characterised by market stability with the leading firms maintaining their position through incremental innovation. Scenario HO corresponds rather well with this sequence of events which results in unassailable market position. On the contrary, scenario MS is characterised by a bipolar structure which makes the dominant design compatible with a market niche. This configuration is consistent with the analysis made by Windrum and Birchenhall [34].

Although we do not develop this section further, in order to concentrate on the standard impacts, a detailed examination of both structures, based on individual series of simulation, has highlighted important forces behind the dynamics of the system [35]. In summary, the intensity of competition that prevails across the leader firms on the most demanded

[7] A complete report of the model, including equations and computer programming of the model, can be provided on request.

[8] Over a battery of 50 simulation runs, we have observed four specific cases which were characterised in the long run by a domination of firms specialised in economic performances and that had changed paradigm. The low frequency of apparition of this type of situation led us to focus on the analysis of the two other more frequent cases.

characteristics, the capture of a leader group of green users and the early change of paradigm tend to condition the emergence and survival of the green market niche.

In the following section we consider four different cases depending on the nature of the standard, i.e. depending whether its application concerns the process or the product, and on the timing of intervention. Two periods (100 and 200) have been considered so as to take into account the differentiated stability situation of the industrial structure at these dates. At time 100, whether the scenario HO or MS is being considered, the industrial structure is characterised by a relatively low degree of concentration and the firm's specialisation is not yet established. Thus, the use of tighter standards at this date can be considered as occurring relatively early. On the contrary, at time 200, the industrial structure appears to have stabilised in both scenarios HO and MS. We examine the impact of tighter standards that are twice as much as those initially enforced. This means a level of 3 for process standards and a level of 4 for product standards.

4.2.3 The role of emission standards

Environmental policies rely largely on a regulatory normative approach by which public authorities impose some environmental objectives on the private actors. In general, regulation suffers from an inability to take into account the specificity of individual firms, and for this reason will generally not lead to the lowest cost solution. Modern regulation, however, such as in the context of the European acidification strategy or the national emissions-ceilings directive, often tries to take account of economic constraints such as investment cycles, available abatement technologies, and so on, in order to limit the burden for the regulated industries. Unlike market-based approaches, regulation does not give firms incentives to outperform whatever standard is set for them. Nevertheless regulation may be the preferred choice when it is necessary to avoid 'hot spots' of local pollution, or when it is imperative that a particular objective be met exactly.

Depending on the way regulation is designed, based for example on technology-forcing or performance standards, possibilities for adaptation will be different for firms. Indeed, technology-forcing standards set the technical means to reduce environmental impacts of some production activity whereas performance standards set environmental objectives to be reached within a given deadline, at the risk of incurring financial penalty, but giving enterprises the choice of how to achieve environmental targets. By setting up performance standards, public authorities 'force' firms to undertake significant effort so that the resulting innovation output could serve to formulate emission limit values, thus taking into account the progress made. Such standards play an important role in convincing companies that regulatory authorities will force laggards to react and consequently they are conducive in establishing a climate where firms consider innovation an integral part of their response to the global objectives set by the regulator.

Given that emission standards are characterised by some flexibility regarding the means to achieve environmental targets, we focus on this category of standards. In our model, two types of performance/objective standards are distinguished: at the product level and at the process level.

- Emission standards during the product use: such standards correspond to legislative requirements that target the environmental performance of products (such as passenger car emissions or recycling of end of life vehicles) and that lead producers to take into account polluting impacts of the product during its use or end-of-life phase. Thus tighter environmental standards for the product can be interpreted as tighter regulation regarding the product use or end of life or regarding the production process of the client. They can refer to some limitations of polluting discharge during the product use, to the substitution of harmful substances for the environment or health or to recycling targets for end-of-life products.

– Emission standards during the production process: such standards apply in the case where clients put pressure on their suppliers so that they comply with emission standards during the production of the intermediary good. Clients aim to protect themselves against possible questioning of their product by assuring that their subcontractors are complying with regulations. The example of the Volvo Company illustrates how environmental demand of an industrial client is transmitted through the specifications addressed to its subcontractors. Indeed the automotive manufacturer has informed the whole set of its subcontractors that, given the company’s commitment, environmental certification is becoming compulsory for subcontractors in order to retain their contracts. Thus involvement in a contractual agreement with the client depends on the subcontractor achieving regulatory targets concerning its own production activity.

In the model we present below, requirements of environmental performance enforced by regulation and transmitted through demand on suppliers of intermediary goods are represented by two variables: PerfMinIp and PerfMinIm. We assume that initially these pressures are exerted homogeneously. But they are likely to evolve heterogeneously under the differentiated impulse of clients’ demand. The variables PerfMinIp and PerfMinIm which both characterise demand of environmental quality in our model play a role at three different levels:

– They justify the client’s decision to leave a supplier when they replace the intermediary good. The number of defections is is proportional to the requirement levels of environmental quality since clients will only choose stable relationships with suppliers when they have achieved regulatory compliance.

– They orient R&D activities of suppliers toward environmental R&D. Indeed, suppliers record which characteristics are underdeveloped regarding the minimum requirements of their buyers. This is taken into account in the R&D activities of suppliers.

– They contribute to raise the levels of environmental quality that are required by the group of clients with high sensitivity toward environmental protection criteria. Indeed, the variables PerfMinIp and PerfMinIm change according to the average environmental performance of industry weighted by market shares and according to clients’ preferences. The effect of environmental quality demand on the adjustment function of requirements depends on the firm’s activities of environmental innovation and on the sensitivity of clients toward environmental characteristics.

In the reference configuration, we have considered the following initial values for PerfMinIp and PerfMinIm: 1.5 and 2 respectively, similar for the whole set of clients. We propose to study the impact of a tighter regulation upon the industrial dynamics associated with the scenarios HO and MS.

4.2 The impact of emission standards at the product level

4.2.1 HO scenario

In the HO case, the introduction of a tighter environmental standard at the product level leads to an increase in industrial concentration in the long term (cf. figure 3).

The introduction of the standard leads, through demand requirements, to a transitory increase in the average rate of R&D investment dedicated to environmental quality of the product. An increase such as this leads to improve the environmental performances of the industry (cf. figures 4 and 5) proportional to the rise in environmental quality requirement levels of the whole clients. Though transitory, the reallocation of R&D budget toward the environmental characteristic of the product gives an advantage to those firms with competence cumulated in this field. They can reach the new requirement levels faster. The tightening of regulation mainly contributes to increase market opportunities for firms with strong environmental competencies. These firms can perform some product differentiation on the environment and so they can keep away from strong price competition. The introduction of the standard also operates a selection among the leader firms on price, that target clients with a high sensitivity on price but a low one on the environment.

We note that the product standard favours paradigm change of firms since they succeed in improving the environmental quality of the process along with the product one. In this case, the product standard can represent a lever of action sufficient to allow not only an improvement of the product environmental quality but also a significant improvement of the process environmental quality.

Simulation results show that the introduction of standard at time 100 makes it possible for an ENVI-type firm to survive in the long run. On the contrary, the application of standard at time 200 is too late to allow such market differentiation. Figure 6 illustrates the impact of a tighter product standard upon trajectories of product performance (Am) of an ENVI-type firm. The standard enforced at time 100 leads the ENVI-firm to improve the product environmental quality as well as the product performance, which means innovation offsets. Such innovation offsets result from an efficient combination between economic and environmental characteristics of the product.

In the HO case, we conclude that the early introduction of a product standard gives the possibility of acting before the emergence of a dominant design which is driven by PROD-type firms, i.e. firms betting on price competitiveness and product performance, and which would represent a lock-in into technological trajectories characterised by low environmental content.

4.2.2 MS scenario

In the MS case, the introduction of a tighter environmental standard at the product level leads to a relative decrease in the degree of industrial concentration in the long run (cf. figure 7). This is due to the survival of imitating firms which follow the leader firms specialised on environment and price. The decrease in concentration allows heterogeneous environmental performances to develop. Figure 8 represents the variation coefficient for the global (product and process) environmental performance of firms over time.

We note that the increase in the diversity of environmental performances is higher for a standard at time 100 than for a standard at time 200. Such increase results from the rise in clients' requirements regarding product environmental quality, which implies a reallocation of R&D investment toward environmental characteristics. Improvements in product environmental quality (Im) depend on the firm's competences that have already been accumulated at the time of standard intervention. In the long run, the increase in diversity leads to higher product environmental quality (cf. figure 9) in comparison to the reference case and also to higher process environmental quality (cf. figure 10), in particular when the standard is applied at time 100 rather than at time 200. However, in the long run the level of diversity is lower since firms reach the limits of technological potential faster.

The main beneficiaries of a tighter product standard are the followers, i.e. those firms able to achieve a particular global performance high enough to attract and keep clients with higher requirement levels. The presence of imitators is associated with a decrease in the market shares of the leader firms. Thus the situation of local monopoly achieved by leader firms thanks to their specialisation tends to be questioned. However the leader firms continue to benefit from a first-mover advantage.

We note that ENVI-type firms are the only ones to change paradigm. In other words, whatever the timing of intervention, a tighter product standard has no effect on the paradigm change of PROD-type firms.

In the MS case, we conclude that the introduction of a tighter product standard allows the survival of follower firms that lie behind the specialised leaders and is associated with an increase in the diversity of environmental performances. However, the resulting increase in product environmental quality does not simultaneously lead to an improvement in the process environmental quality that could be high enough for PROD-firms to experience a paradigm change.

4.3 The impact of emission standards at the process level

4.3.1 HO scenario

The introduction of a tighter environmental standard at the process level leads to an increase in the market shares of ENVI-type firms in the long run. Indeed the cumulated market shares of ENVI-type firms during the last period is 4% when the standard is applied at time 100 and 23.5% when the standard is introduced at time 200 whereas this share is zero in the reference case.

The introduction of the standard has few effects on the degree of concentration. However, it significantly affects the characteristics of clean technologies. The introduction of the standard at time 100 leads all firms, especially the PROD-type ones, to change paradigm, which is associated with an improvement of the average environmental quality of the process (Ip) (cf. figure 11). Competition thus takes place between firms with different specialisation but all progressing in the green paradigm. The late application of the standard at time 200 strongly punishes the firms that are below the new regulatory requirements and that do not possess the sufficient capabilities to close the gap. This induces a progressive decline of their market shares and leads them to exit the market. However, the late introduction of a process standard does not enable all firms to change paradigm. Indeed, some PROD-type firms locked in the first paradigm are able to survive in the long run even if their market shares tend to decline in the last periods.

From figure 12, we note that the tightening of the process standard has a positive effect on the environmental quality of the product, in particular if the standard is introduced early. Figure 13 shows the impact of the process standard on the evolution of the process characteristics of a PROD-type firm. We note that the process standard leads the firm to change paradigm. When the standard is applied at time 100, the productivity level of the firm is close to the upper limit set in the green paradigm. On the contrary, when the process standard is introduced at time 200, the productivity level is lower in the long run but it is associated with a higher process environmental quality. Figure 14 shows that the process standard at time 100 also leads the PROD-firm to reach a very high level of product performance. Thus, the late introduction of a process standard leads to a decrease in the economic performance of PROD-firms since they are forced to invest in environmental R&D to meet the user's needs.

In the HO case, the impact study of a tighter process standard raises the following conclusions:

- The early application of the standard leads to the paradigm change of all firms and contributes to the emergence of a market niche. However the survival of the market niche is weakened by the price competition of rival firms in the green paradigm. The standard also leads to a strong improvement in the average environmental quality of the product in the industry.

- The late introduction of the standard occurs when the firm's specialisation is well established and competition is strong between PROD-type firms. The application of the standard jeopardises the PROD-type firms that have not accumulated strong environmental competencies. This explains their difficulty to quickly reallocate their research activities towards the improvement of process environmental quality and their resultant lag in complying with the new standard.

4.3.2 MS scenario

Simulation results show that the late introduction of a tighter process standard leads to an increase in the average process environmental quality (cf. figure 15) that leads to firms shifting towards the green paradigm.

Figure 16 shows that there is a higher impact on the environmental quality of the product if there is a late introduction of the standard compared to introduction during a non stabilised stage of the industrial structure.

The introduction of the standard at time 200 contributes to increased market opportunities for firms achieving intermediate economic performance (price and product quality) compared to the specialised leaders (cf. figure 17).

On the contrary, the process standard at time 100 initiates strong instability in the supplier-user relationships due to a low differentiation in the supply of firms. This prevents buyers from selecting appropriately the suppliers and prevents suppliers from exiting the market. In the simulation, only one ENVI-type firm succeeded in differentiating and achieving a relatively stable market share of 25%. The remaining market is shared by the other firms. In spite of the high requirement level of process environmental quality enforced at time 100, only two firms succeed in changing paradigm in the long run. In fact, the increase in client demand for process environmental quality –resulting from the new standard- contradicts the predominant pressure of clients on price. From period 100, competition tends to be centred on product performance (Am) thanks to strong demand and to low minimum requirements of all clients. This gives rise to an increase in the average rate of R&D investment dedicated to this attribute.

The higher level of competition on the product performance increases client requirements on this attribute, which limits all the more the possibilities for reallocating R&D towards other characteristics. In this case, the R&D level allocated to the environmental characteristic of the process is insufficiently high to innovate on this dimension, which thus jeopardises the possibilities to progress on this dimension.

Figure 18 represents the trajectory of a leader PROD-type firm in the three cases considered. Figure 18 illustrates that progress on productive efficiency is limited by the introduction of the standard at time 100. In this case, the maximum level reached at the last period is 6.41 for a process environmental quality of 2.22. On the contrary, when the standard is applied at time 200, the leader PROD-type firm is not only close to the upper limit prevailing for this dimension (14) with a score of 13.81 but it also achieves a level of process environmental quality of 3.51, i.e. it succeeds in changing paradigm.

From an environmental point of view, the increase in process environmental quality requirements resulting from the late application of the standard is more efficient as it enables higher levels of environmental and economic performance to be reached. In other words, in the MS case, the late enforcement of a process standard, i.e. in the stabilisation stage of the industrial structure, leads to innovation offsets.

4.4 Discussion

Table 3 gives a summary of the results.

Insert table 3

From this set of results, we draw the conclusion that the rise in the environmental requirements of clients, generated by tighter environmental standards, has different impacts according to the nature and timing of the standards:

- A tighter product standard enables a greater increase in the average environmental quality of the product if it is enforced early rather than late. The product standard has also a positive side-effect on the process environmental quality. In particular, if an exclusive dominant design emerges on the market because of strong competition between PROD-type firms, the early application of the product standard leads to a shift in paradigm for firms.

- A tighter process standard enables an increase not only in the average process environmental quality but also in the average product one. The early application of the standard tends to be more efficient in the case of an homogeneous oligopoly dominated by PROD-type firms.

- On the contrary, in the case of a market segmentation characterised by the emergence of a green market niche the late application of a tighter process standard allows higher levels of environmental and economic performance to be reached.

Finally, the results exhibit that in the scenario of an exclusive dominant design, independent of the type of standards, it is important to act relatively early before the specialisation of leader PROD-type firms has stabilised, which allows firms to take action before the lock-in into a technological path with low environmental content. In the scenario of coexistence of a dominant design and a green market niche, it is important for the product standard to be implemented prior to the process standard in order to enable the followers to survive and to encourage innovation offsets for firms. In such cases, emission standards may prevent both a situation of lock-in on the supplier side and a situation of behavioural inertia on the user side. Standards may thus enable a preservation of certain forms of technological and behavioural diversity.

Conclusion

This paper gives an analysis of tighter environmental standards on the basis of a model of industrial dynamics. The model studies the evolution of two populations of vertically related firms that have to cope with environmental quality demand. In the reference configuration we have considered, it is shown that market forces do not necessarily drive the economic system along sustainable development paths and do not preserve open options long enough. In particular, the pressure exerted on the price by the clients and sustained by the upstream competition between suppliers can jeopardise the survival of a green market niche that yet allows protecting variation. Standards can thus be helpful in supporting the dynamics of innovation and in avoiding premature lock-in. From the simulation trials, we show that the efficiency of standards depends on the nature of performance standards (process or product), on the market structure and on the timing of intervention. Such results stress the different efficiency of regulatory instruments according to the evolution of industrial structures across time. Moreover, results show that tighter emission standards not only play a significant role in orienting research and innovation activities of supplier firms, but they are also likely to support the diffusion of environmental innovation in the supply chain.

From the perspective of sustainable development, great attention has been given to initiatives on further development of clean technologies. The model calls for public intervention that should simultaneously emphasise technological development and demand policies that induce more environmentally-conscious production and use patterns. Co-ordination of innovation and environmental policies within vertical inter-firm relationships should be further examined.

Finally, it is important to underline the preliminary nature of the results reported here. First, it is necessary to increase the robustness of the model and this can be achieved by considering a simpler version with a smaller number of parameters. Second, our model considers a generic industry without emphasising differences and regularities that exist in the sectors (as highlighted in the works of Pavitt or Malerba). Better specifications would lead to a clearer understanding of the diversity among sectors and would allow the study of the coevolutionary processes underlying their dynamics in order to explain sectoral differences on environmental performance.

Appendix: Initial values of parameters in the reference configuration

Table 1: Parameter values

Parameter	Value
Initial number of suppliers	n=12
Initial number of clients	m=200
Requirement level parameter	$\varepsilon = 0.01$
Perception degree of environmental quality	$\sigma = 0.25$
Sales effect on R&D index	$\alpha = 0.01$
Relative importance of positive score	$\beta = 0.09$
Characteristic-specific R&D rate	$\delta^h = 0$
Experience level	$E^h = 1$
R&D rate on turnover	$\mu = 1$
Research level	$R^h = 0$
Initial performance level	$X^h = 1$
Initial price	$P = 3$
Initial R&D index	$RDIndex^h = 0$
Speed parameter for experience	$\lambda = 0.01$
Speed parameter for research level	$\gamma = 0.1$
Mark-up rate	$\theta = 200\%$
Initial market shares	$MS = 1/12$
Upper product performance bound	$X^{2\max} = 14$
Lower product performance bound	$X^{2\min} = 1$
Productive efficiency threshold in paradigm 1	$X^{1\max 1} = 4$
Upper productive efficiency bound	$X^{1\max 2} = 14$
Upper bound of process environmental quality in paradigm 1	$X^{3\max 1} = 3$
Upper bound of process environmental quality in paradigm 2	$X^{3\max 2} = 13$
Upper bound of product environmental quality	$X^{4\max} = 14$
Scale parameter for innovation output	$\eta_0 = 0.01$
Innovation elasticity of research level	$\eta_1 = 0.45$
Innovation elasticity of experience	$\eta_2 = 0.1$
Innovation elasticity of distance to the upper bound	$\eta_3 = 0.45$
Maximum experience level	$MaxE = 3$
Minimum sales	$N^{\min} = 1$
Parameter of the innovation probability	$\pi_1 = 0.035$
Parameter of the innovation probability	$\pi_2 = 0.05$
Parameter of the innovation probability	$\pi_3 = 0.65$
Parameter of the innovation probability	$\pi_4 = 0.4$
Bandwagon effect	e=0.1

Table 2: Typology of user groups in the reference configuration

Profile	User group G1	G2
Weight assigned to price	$x^1 = 0.05$	$x^1 = 0.45$
Weight assigned to product performance	$x^2 = 0.05$	$x^2 = 0.45$
Weight assigned to process environmental quality	$x^3 = 0.45$	$x^3 = 0.05$
Weight assigned to product environmental quality	$x^4 = 0.45$	$x^4 = 0.05$
Maximum price	$levelX^1 = 4$	$levelX^1 = 1$
Minimum requirement level for product performance	$levelX^2 = 2$	$levelX^2 = 2$
Minimum requirement level for process environmental quality	$levelX^3 = 1.5$	$levelX^3 = 1.5$
Minimum requirement level for product environmental quality	$levelX^4 = 2$	$levelX^4 = 2$
Initial proportion	20%	80%

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Figure 1: Supply-Demand Interactions

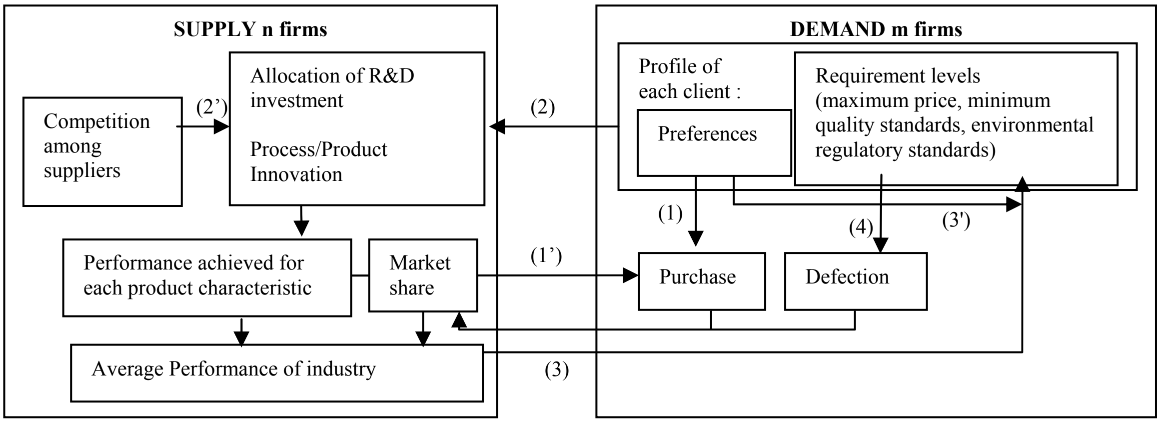


Figure 2: The space of technological and environmental opportunities in the model

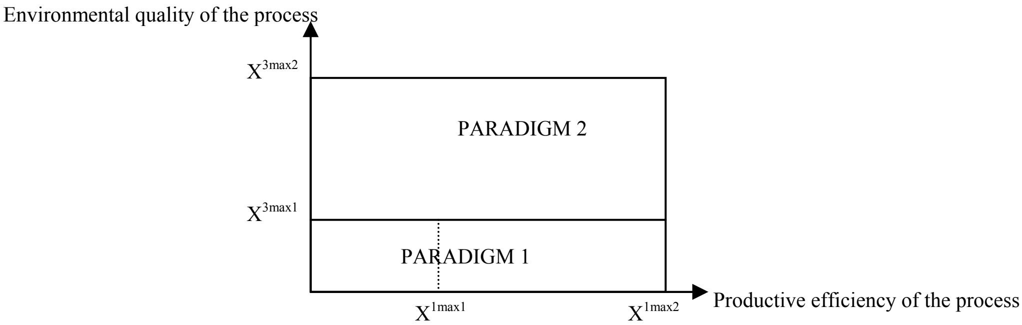


Table 3: Impacts of tighter standards (levels twice as much as initially): summary of the results

<table>
<tr><th rowspan="2">Type of standard</th><th rowspan="2">Scenario of industrial dynamics</th><th colspan="2">Timing of intervention</th></tr>
<tr><th>T=100</th><th>T=200</th></tr>
<tr><td rowspan="4">Process standard</td><td rowspan="2">Scenario HO</td><td colspan="2">Increased market shares of ENVI-type firms
No effect on the concentration
Positive effect on product environmental quality</td></tr>
<tr><td>Paradigm change of PROD-type firms
Competition within the green paradigm
Improvement in average process environmental quality
Higher impact on product environmental quality</td><td>Market segmentation
Negative effects on the economic performance of PROD-type firms</td></tr>
<tr><td rowspan="2">Scenario MS</td><td colspan="2">Increase in environmental performance of industry (process and product)</td></tr>
<tr><td>Strong instability in buyer-supplier relationships
Negative side-effect on the productive efficiency improvements</td><td>Increase in average process environmental quality
Partially favours paradigm change
Higher impact on product environmental quality
Innovation offsets</td></tr>
<tr><td rowspan="4">Product standard</td><td rowspan="2">Scenario HO</td><td colspan="2">Increase in concentration
Improvement in environmental performance of the industry
Paradigm change</td></tr>
<tr><td>Market differentiation favouring ENVI-type firms
Innovation offsets</td><td></td></tr>
<tr><td rowspan="2">Scenario MS</td><td colspan="2">Relative decrease in concentration
Survival of imitators
No effect on paradigm change of PROD firms</td></tr>
<tr><td>Higher increase in the diversity of environmental performance
Higher process environmental quality
Higher product environmental quality</td><td></td></tr>
</table>

Impact of tighter product standards in the scenarios HO and MS

Figure 3: scenario HO

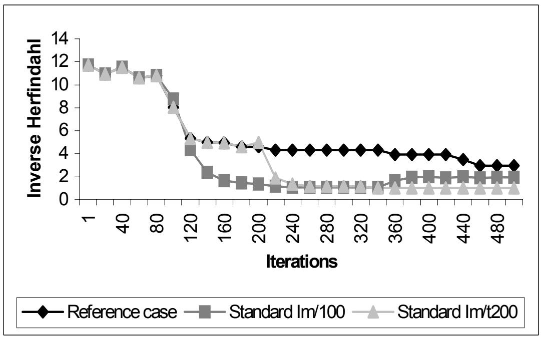


Figure 4: scenario HO

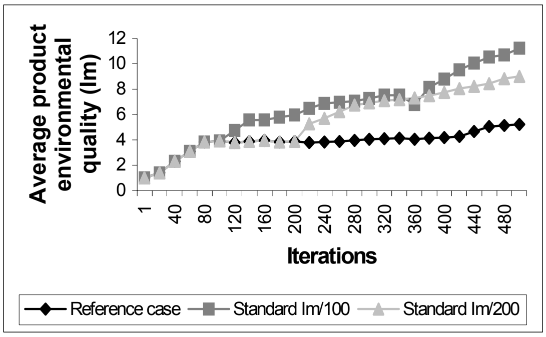


Figure 5: scenario HO

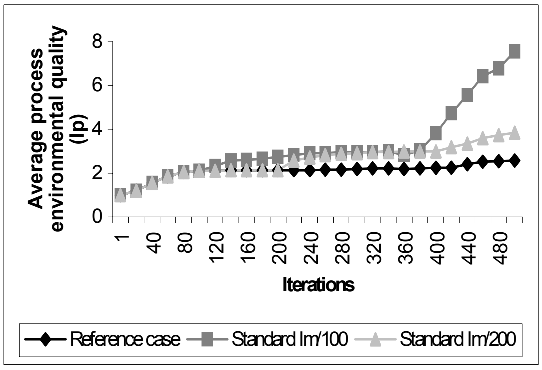


Figure 6: scenario HO

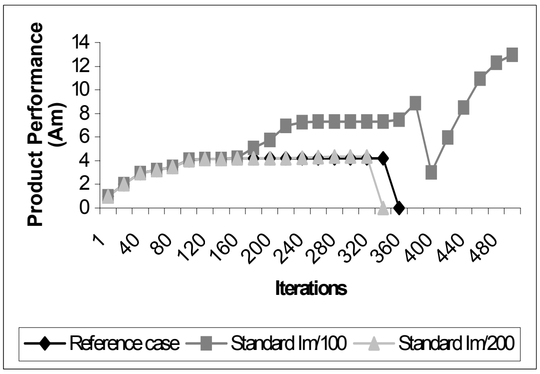


Figure 7: scenario MS

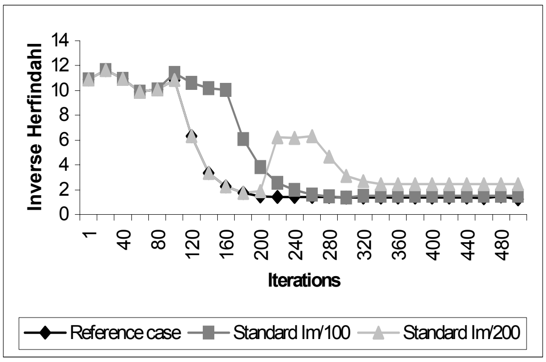


Figure 8: scenario MS

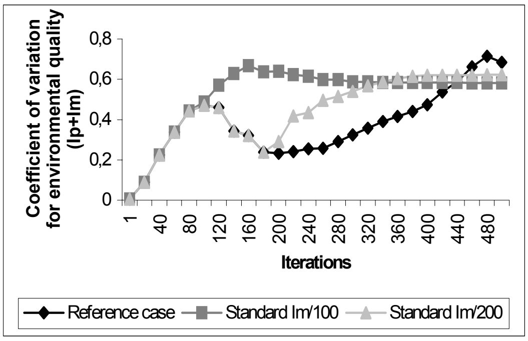


Figure 9: scenario MS

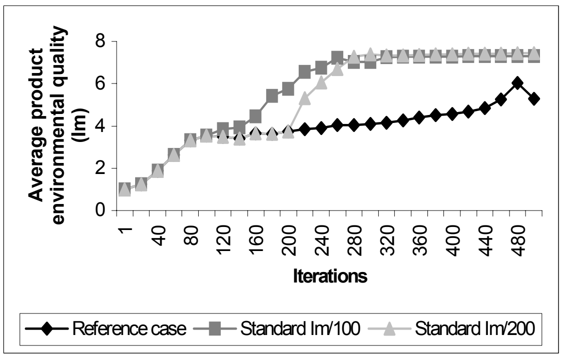
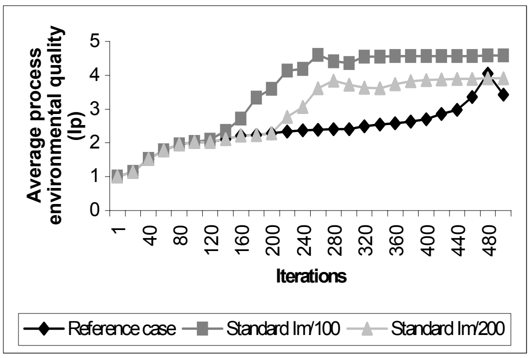


Figure 10: scenario MS



Impact of tighter process standards in the scenarios HO and MS

Figure 11: scenario HO

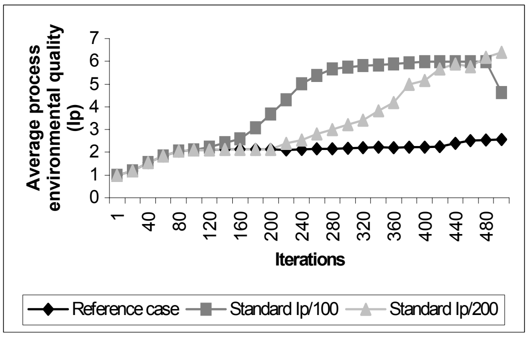


Figure 12: scenario HO

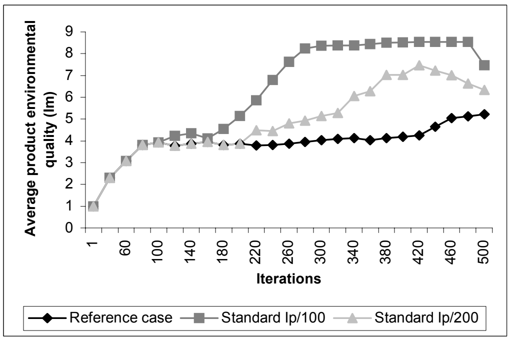


Figure 13: scenario HO

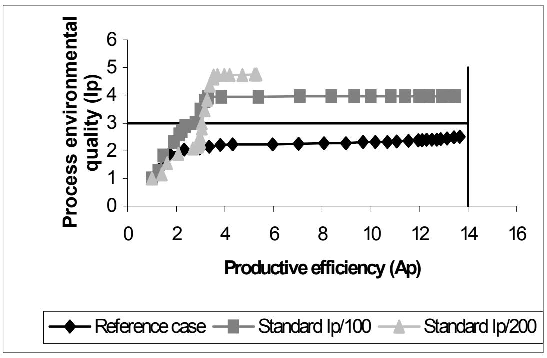


Figure 14: scenario HO

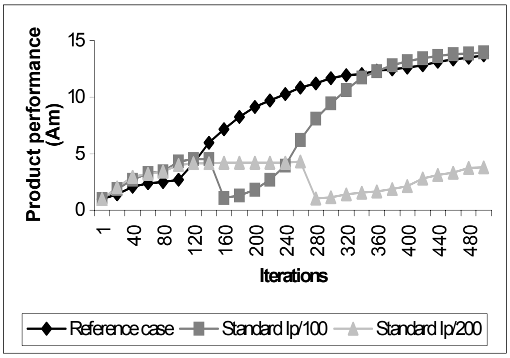


Figure 15: scenario MS

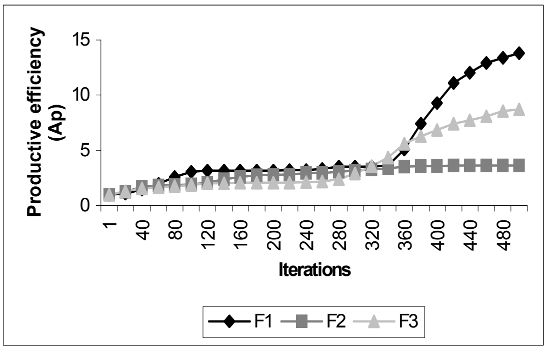


Figure 16: scenario MS

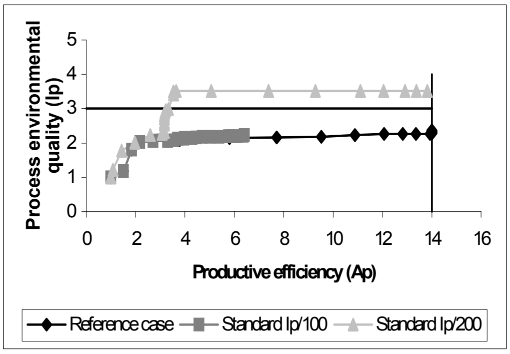


Figure 17: scenario MS

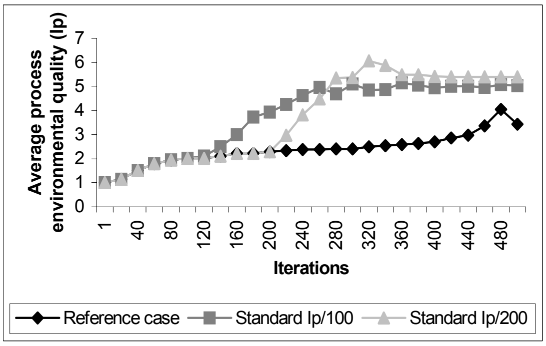
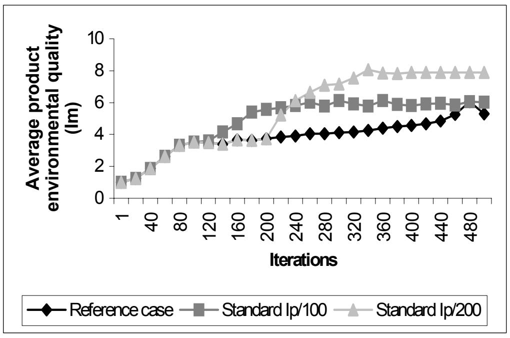


Figure 18: scenario MS



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